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EFFECTIVE CALIBRATION OF HEAT FLUX TRANSDUCERS FOR EXPERIMENTAL USE

U S ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE

Natick, Massachusetts

JANUARY 1990

UNITED STATES ARMY
MEDICAL RESEARCH & DEVELOPMENT COMMAND

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A method of calibrating heat flux transducers (HFTs) using the USARIEM Hohenstein skin model system is described. A representative sample of the currently available types of HFTs were tested and their results confirmed that the factory supplied calibration constants should not be used for collecting experimental data. The HFT application procedure described in this report must also be subscribed to for attaching the HFT on human subjects. The adherence to a standard procedure ensures that the newly recalibrated constants are applicable, and avoids as much as possible any extraneous steps where error could be introduced. Employing this standard attachment method, the newly calibrated HFT constants were found to deviate from the factory supplied values by as much as 24%. It is recommended that heat flux transducers be recalibrated before each protocol study using techniques described in this report with the Hohenstein skin model.

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EFFECTIVE CALIBRATION OF HEAT FLUX TRANSDUCERS FOR EXPERIMENTAL USE

by

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ABSTRACT

A method of calibrating heat flux transducers (HFTs) using the USARIEM Hohenstein skin model system is described. A representative sample of the currently available types of HFTs were tested and their results confirmed that the factory supplied calibration constants should not be used for collecting experimental data. The HFT application procedure described in this report must also be subscribed to for attaching the HFT on human subjects. The adherence to a standard procedure ensures that the newly recalibrated constants are applicable, and avoids as much as possible any extraneous steps where error could be introduced. Employing this standard attachment method, the newly calibrated HFT constants were found to deviate from the factory supplied values by as much as 24%. It is recommended that heat flux transducers be recalibrated before each protocol study using techniques described in this report with the Hohenstein skin model. (AW)

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INTRODUCTION

Cutaneous heat flux data provide important information when evaluating the effectiveness of chemical protective antidotal drugs and assessing physiological responses during heat and cold environmental stress. Presently four types of heat flux transducers (HFTs) are available at the Military Ergonomics Division, USARIEM. They will be designated as type C, H, R and T in this report. Each presents a unique configuration and construction. All HFTs are provided with calibration constants by the manufacturer. However, it is widely known that the manufacturer supplied calibration constants are not wholly reliable, and periodic recalibrations of HFTs are necessary [Nuckols and Piantadosi, 1980]. Also, since the HFTs are almost always used with some type of thermally conductive gel, it's reasonable to suspect that the factory supplied calibration constants of bare HFTs are no longer applicable in the experimental study settings. Until recently, no technique for the recalibration of HFTs was available at USARIEM. This report describes a universal method of HFTs recalibration using a recently acquired Hohenstein skin model system at the Military Ergonomics Division, and establishes a standard procedure of HFT placement on human subjects.

MATERIALS and METHODS

Heat Flux Transducer

A heat flux transducer typically consists of a solid slab of homogeneous material with thermopiles on each side, as shown schematically in Figure 1. The solid slab has a well defined thermal conductance, G_S ($W \cdot m^{-2} \cdot K^{-1}$). A temperature gradient of ΔT_S (°C or K) across the slab produces a heat flux $\dot{Q}$ ($W \cdot m^{-2}$) of:

$$\dot{Q} = G_s \bullet \Delta T_s \quad (1)$$

The thermopiles detect the temperature difference and generate a voltage potential (usually in the millivolt or microvolt range), proportional to ΔT_s, across the slab. Hence, by measuring the voltage, heat flux $\dot{Q}$ can be computed using Equation 1. The commercially available HFTs combine G_s and the voltage-temperature conversion factor into a single value, which is then provided as the transducer calibration constant.

The four types of HFTs available each represent a different construction and configuration. Table 1 shows their physical characteristics.

Hohenstein Skin Model

The Hohenstein skin model measures the heat transfer from a horizontal, heated, constant temperature flat plate up through a layer of test material into a cooler ambience. The model is housed in a climatic chamber where a constantly circulating airflow maintains the chamber temperature at a level set from a front panel control dial. The skin model itself consists of a square measuring section (head plate) 20cm x 20cm, composed of porous sintered metal. The head plate is surrounded by a brass guard section (guard ring) 9cm wide on each side (see Figure 2). The head plate and guard ring are coplanar. In operation, both sections are electrically heated and maintained at the same temperature (35°C). The guard ring prevents lateral loss of heat from the head plate, thereby ensuring a unidirectional flow of heat vertically upward into the cooler chamber air stream.

The amount of power (W) required to maintain the head plate at the designated temperature is displayed on front panel displays, as a voltage and a current. The required power divided by the known head plate surface area ($0.04m^2$) gives the power density (W/m^2) dissipated by the head plate. This power density will be used in computing the new HFTs calibration constants (see Equation (2)). The head plate is also capable of simulating a sweat-wetted surface by evaporating distilled water, a capability not used in the HFTs calibration procedure. In addition to temperature control, the climatic chamber also permits humidity and air velocity adjustments from front panel control dials. A more detailed description of the skin model and its operations can be found in the Hohenstein skin model operation manual.

Heat Flow Transducer Placement

The method and procedure of HFTs placement on the head plate duplicates *in situ* their placement on human subjects. A copious amount of surgical lubricant was used between the HFT surface and the skin (or the head plate surface). The lubricant eliminated air gaps between the two surfaces and provided a thermally conductive interface. On human subjects, the HFTs are generally affixed on the skin using plastic adhesive tape. The adhesive tape should be approximately four to five times the surface area of the HFT, to ensure a firm placement. There should not be any air gap between the HFT surface and the adhesive tape. Similarly, for the calibration procedure, a piece of the same type of plastic adhesive tape covered the HFT. Therefore, this recalibration procedure actually measures the calibration constant of the entire ensemble of plastic

adhesive tape, HFT, and surgical lubricant, and not simply the HFTs themselves. Since the HFTs are never used without the lubricant and the adhesive tapes, calibration of the bare HFT is not entirely useful. It's much more practical and realistic to obtain the calibration value of the entire assembly.

Calibration Procedures

For the HFTs calibration, the head plate and guard ring were maintained at 35°C. The chamber temperature was adjusted to different levels to create different temperature gradients between the head plate and the chamber. The chamber air velocity was 1 m/s. Chamber relative humidity was set at 40%, although the humidity level does not affect the HFTs calibration values since sensible heat flow is the variable measured.

Calibration using the skin model presents a unique complication. The lubricant gel could not be applied directly onto the plate surface area, as it would clog the pores in the head plate and impair the skin model's ability to simulate sweating conditions. Hence, a 10 micron thick polyester membrane was used between the HFT and the head plate, to keep the lubricant from the head plate surface. Although not essential to the present calibration procedure, the polyester membrane has a hydrophilic property which allows water vapor to evaporate through, but prevents water droplets from penetrating. Using a membrane complicates the recalibration process and changes the thermal characteristics of the HFT ensemble. The thermal resistance of the membrane must be obtained, and properly accounted for in computing the new calibration values.

First, the baseline power requirement of a bare head plate was measured. The chamber temperature was set to 10°C, 15°C, 20°C, 25°C, 30°C, and 35°C. The power density (W/m^2) needed to maintain the head plate (and guard ring) at 35°C, at each of the chamber temperature setting is shown in Figure 3. Figure 3 shows that the power density requirement was a linear function of the temperature gradient (ΔT_g). It is assumed that because the HFTs surface areas (see Table 1) are small compared to the total head plate surface area, hence placing a heat flux transducer on the head plate does not affect the total power dissipation of the head plate.

Next, the head plate area was covered with a 10 micron thick polyester membrane. The membrane was stretched taut across the head plate to eliminate trapped air. With the polyester membrane installed, another head plate baseline measurement was performed. The membraned head plate yielded a dissipated power density that was on average 6.7% less than the bare plate condition (see Figure 3). This 6.7% difference represents a thermal insulative property of the polyester membrane.

After the baseline power measurement, the polyester membrane was removed. It was found that the application of the lubricant gel tended to stretch and wrinkle the membrane, thus during calibration, only a small piece of the membrane was used underneath the HFT to keep the gel away from the head plate. This membrane section was discarded after each calibration, and a new section used for each HFT.

Ten HFTs (three of Type C, two of Type H, three of Type R, and two of Type T) were calibrated individually. For each calibration, the surgical lubricant was

applied to one surface of the HFT. The HFT was then placed flat in the center of the head plate with the lubricated side face down on a small section of the polyester membrane. A slight pressure was applied to the HFT to force the lubricant gel to fill in all the air gaps. The dimension of the membrane section must be slightly larger than the HFT so that the gel does not contact the head plate directly. By convention, orientation of HFT placement was such that a heat loss (from the head plate through HFT to the chamber ambient air) is indicated by a positive HFT millivolt output. The surface temperature of Type C, which has a thermistor incorporated into the HFT, was not measured in this study. A piece of plastic adhesive tape was applied to the upward facing surface of the HFT. In actual human subject testing, the adhesive tape should be approximately four to five times the surface area of the HFT, to secure the HFT on the subject. For the calibration procedure, a smaller piece of tape may be used, since the covered head plate surface area should be minimized. However, the adhesive tape must nevertheless be larger than the HFT, as it also serves to anchor the HFT firmly on the head plate surface.

Four chamber temperatures: 15°C, 20°C, 25°C, and 30°C, were used for the calibration. The sequence of chamber temperature settings was randomly determined, to avoid any possibile pattern adjustment of the HFTs or the skin model system. At each temperature setting, the power consumption was recorded from the front panel display after the chamber has reached the set temperature for twenty minutes to allow equilibrium conditions to be established within the test chamber. The HFTs millivolt (mV) output was measured with a Fluke 8842A multimeter and recorded.

The calibration constants (in $W \cdot m^{-2} \cdot mV^{-1}$) were computed using Equation (2)

$$\text{Calibration constant} = \frac{\text{Power}}{\text{Head plate area} * \text{HFT mV}} \qquad (2)$$

Note in Equation (2), (Power/Head plate area) is the power density term. Since only a small section of the polyester membrane was used underneath the HFT, the head plate power dissipation level shown on the front panel display was essentially that of a bare plate. Therefore, the actual power density dissipated through the HFT must be adjusted to be 6.7% smaller, to account for the membrane insulation. The new calibration constants for the HFTs in Table 2, were taken as the average of the four calibration values from the four temperature settings.

RESULTS and DISCUSSION

The 10°C and 35°C chamber environments were not used for the calibration because of the difficulties encountered during the bare head plate baseline measurement. When the chamber was at 10°C, it proved difficult to maintain the head plate and guard ring temperatures at a constant 35°C. The guard ring temperature often dropped below 35°C and created an unacceptable lateral temperature gradient between the head plate and the guard ring. When the chamber, the head plate and the guard ring were all at 35°C, theoretically, there should not have been any net energy exchange, and therefore power dissipation should be zero. Figure 3 clearly shows a power consumption level, although small, at the 35°C ($\Delta T_s = 0$) environment. There was apparently some minor nonuniformity

in the head plate heating pattern and/or in the chamber airflow. A zero temperature gradient between the head plate and the chamber could not be achieved uniformly over the entire head plate surface, hence the minimum dissipated power indication.

Figure 3 gives the power density data of the bare head plate and the polyester membrane covered head plate. The bare plate data are shown as •, and the membraned plate data are shown as ×. The linear regression equations and the solid and dash lines representing the corresponding linear equations are also included in Figure 3. The power density data from ΔT_s=5°C, 10°C, 15°C, 20°C and 25°C yield an average 6.7% difference in dissipated power density between the bare and membraned head plate.

Table 2 compares the factory supplied calibration constants and the newly calculated calibration values for the ten HFTs tested. The largest deviation was 24%. The deviation values in Table 2 are not a direct indication of the unreliablity of the factory supplied calibration constants, since as mentioned early, the ensemble of lubricant, HFT and adhesive tape was measured as an entirety. Table 2 does nevertheless point out that the factory supplied constants are not wholly appropriate for experimental use because of the manner with which the HFT must be applied.

Our results concur with other reports that periodic recalibration of HFTs are necessary and extreme care must be taken in collecting and applying the HFTs data. [Kuckols and Piantadosi, 1980; Wissler and Ketch, 1982].

CONCLUSION

A standardized method of recalibrating heat flux transducers is now available using the newly acquired Hohenstein skin model system. Testing of a representative sample of the available HFTs revealed that recalibration was indeed necessary as the new calibration values can deviate from the factory supplied calibration constants by as much as 24%. It is recommended that HFTs recalibration be performed before each protocol study by using the Hohenstein skin model and techniques described in this report, and a standardized procedure of HFT placement be adopted, following outlines described in this report.

REFERENCES

1. Nuckols M.L. and C.A. Piantadosi. "Calibration and characterization of heat flow transducers for use in hyperbaric helium." *Undersea Biomed. Res.*, 7(4):249-256, 1980.

2. Wissler E.H. and R.B. Ketch. "Error involved in using thermal flux transducers under various conditions." *Undersea Biomed. Res.*, 9(3):213-231, 1982.

Table 1 Heat flux transducer physical characteristics

HFT Type	Surface Area (cm^2)	Thickness (cm)	Shape
C *	5.07	0.203	circular (2.54cm dia.)
H	1.15	0.150	circular (1.21cm dia.)
R	1.17	0.038	rectangular (1.60cm x 0.73cm)
T	1.82	0.159	rectangular (1.91cm x 0.95cm)

* Type C heat flux transducers contain an imbedded thermistor on one surface.

Table 2 Heat flux transducer calibration values

Type		Factory Calibration Constant $\frac{W/m^2}{mV}$	New Calibration Constant $\frac{W/m^2}{mV}$	Deviation
C	no. 1285	100.6	104.2	+3.58%
	no. 1277	112.6	98.5	−12.5%
	no. 1271	102.8	104.1	+1.27%
H	no. 7656	1314	1209	−7.99%
	no. 7713	1434	1085	−24.3%
R	no. 827	2190	2396	+9.40%
	no. 816	2160	1803	−16.5%
	no. 814	2103	1798	−14.5%
T	no. S176	211.3	252.6	+19.6%
	no. S141	208.2	184.6	−11.3%

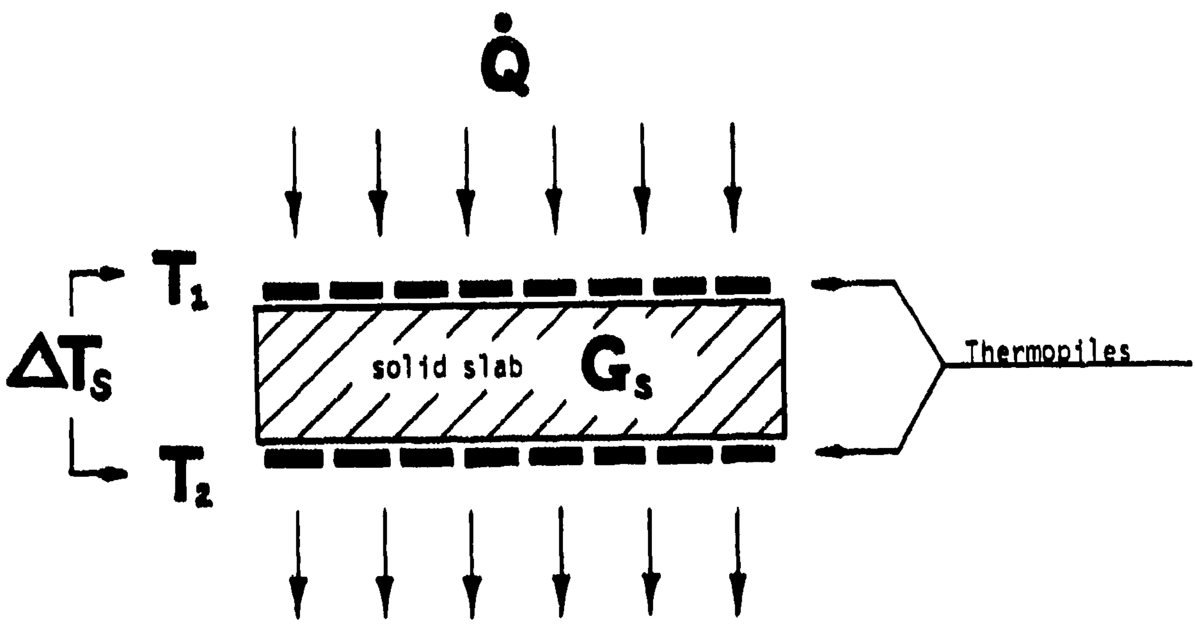


Figure 1 Schematic diagram of Heat Flux Transducer

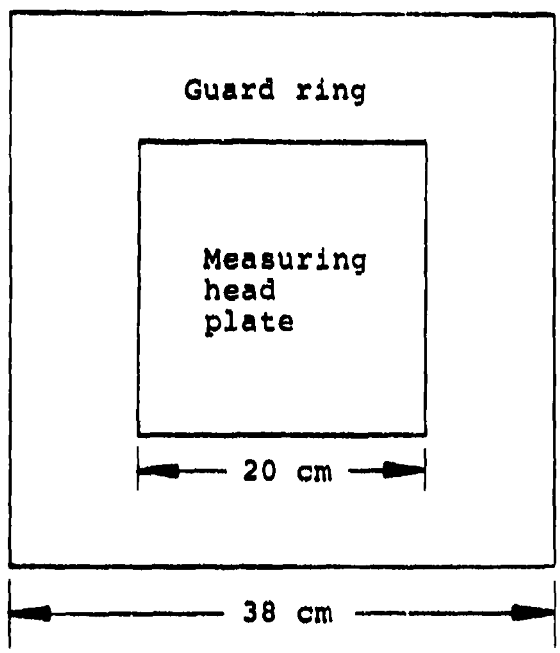
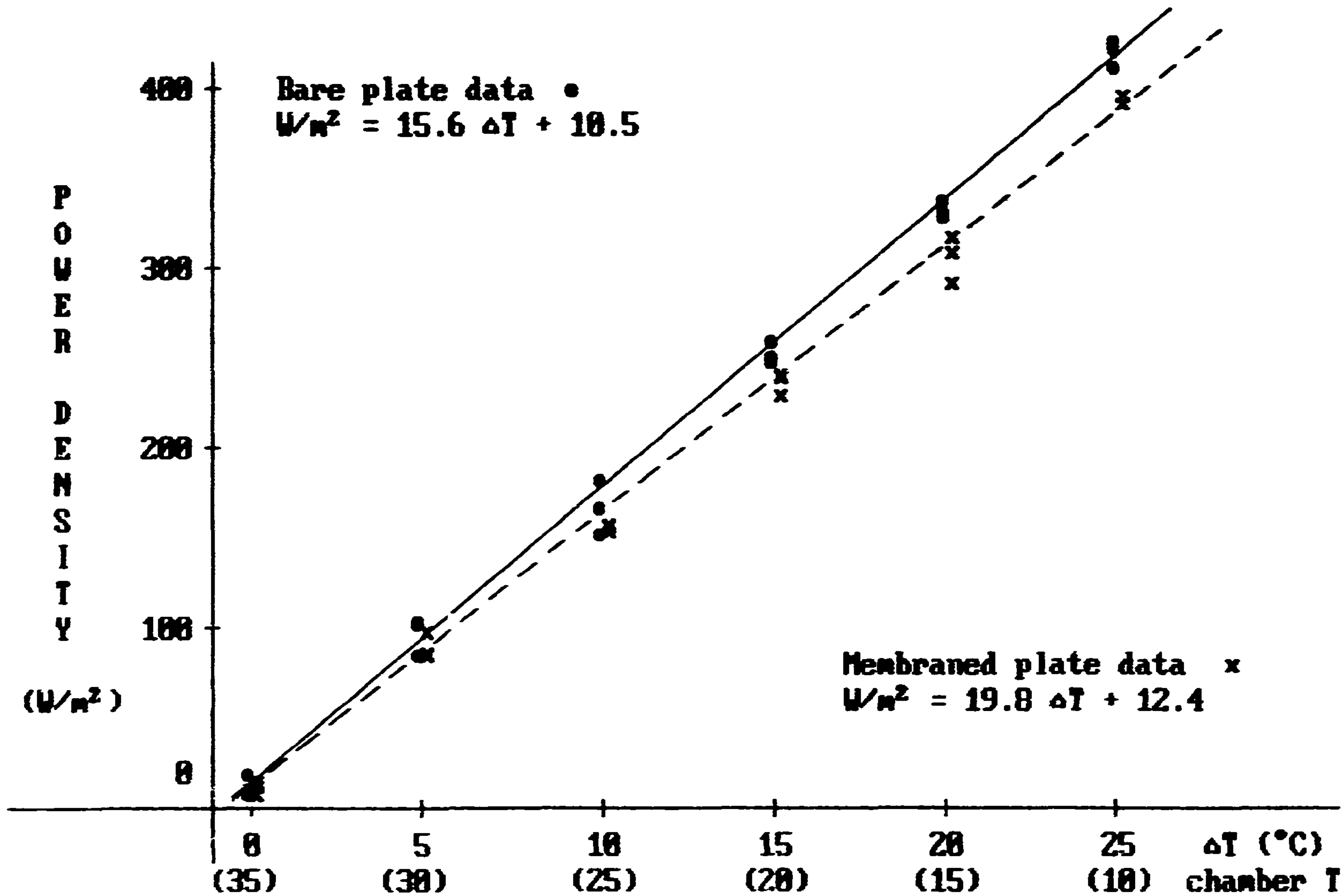


Figure 2 Top view of head plate and guard ring assembly

Figure 3 Baseline power density dissipated by bare and polyester membrane covered head plate
Solid and dash lines represent the corresponding linear regression curves



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SUBJECT: Erratum to USARIEM Technical Report T8-90, "Effective Calibration of Heat Flux Transducers for Experimental Use"

To Whom It May Concern:

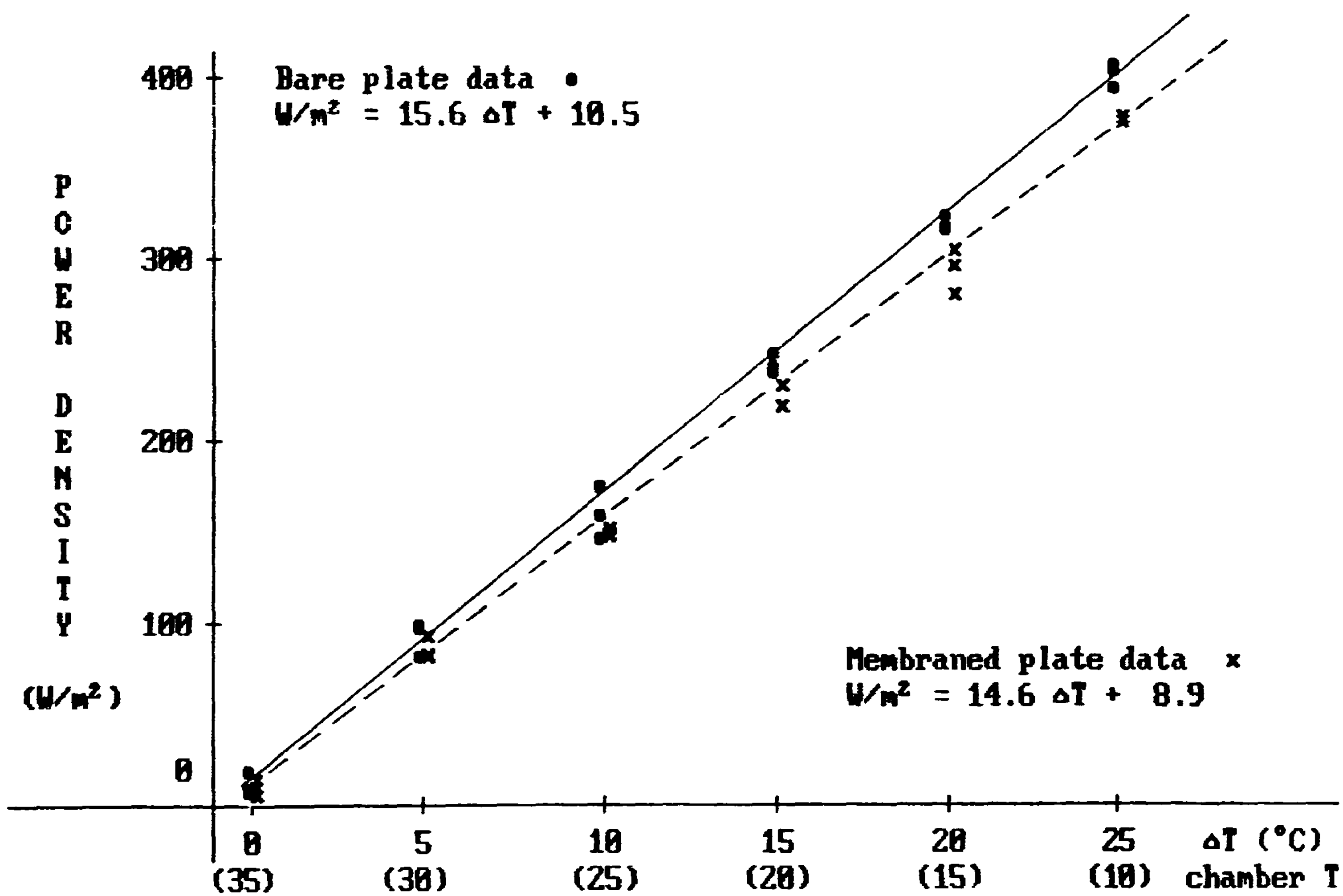
A technical error has been discovered on page 14 in the subject printed work. Accordingly, 12 corrected sheets (pages 13-14) are enclosed which should be included with the copies of the original technical report previously forwarded to your agency.

Sincerely,

Stephen KW. Chang, Ph.D.
Biomedical Engineer

Enclosure

Figure 3 Baseline power density dissipated by bare and polyester membrane covered head plate Solid and dash lines represent the corresponding linear regression curves



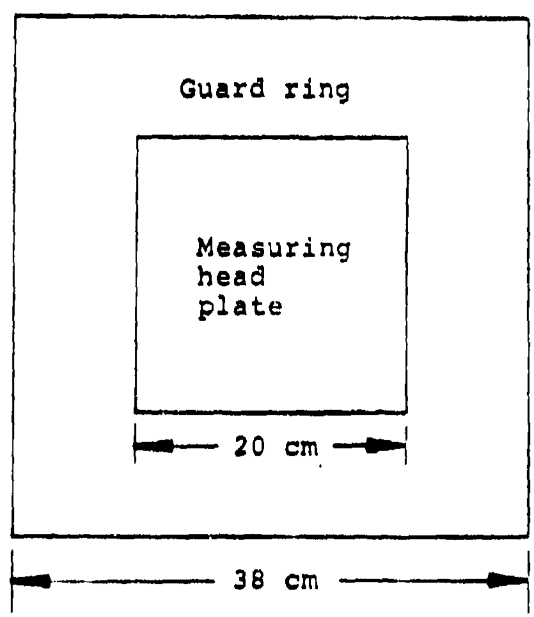


Figure 2 Top view of head plate and guard ring assembly